one part per thousand (1/1000) results in a change of capacitance of approximately one part per million (1/1,000,000); the latter change is a thousand-fold smaller than the former."

The next step in the development of the concept was to modify the capacitor in such a way that its unique properties could be exploited to measure angle. Insulating gaps were cut across the toroids at the zero and 180 degree locations, creating two pairs of semi-circular capacitors as shown in Figure 2. A semi-circular shield was placed between the top and bottom tier of rings, rotating on frictionless air bearings about the central axis. (It is placed at an angle α from the shield's leading edge to the insulating gap in the Figure.) Because the shield is grounded, the capacitance of the ring portion that it covers is eliminated. Only those parts of the ring not covered by the shield, indicated by $C_1 = C\alpha$ and C_2 $C(\pi - \alpha)$ can act as capacitors (C is the capacitance per unit angle).

The two capacitors were then placed in series in an alternating current bridge circuit, as shown in Figure 3. Because a capacitor offers resistance to an alternating current, there is a voltage drop across each of the capacitors. From Ohms law it can be shown that the ratio of the voltages V_o over V_i is equal to the ratio of the capacitances C_2 over $(C_1 + C_2)$, and that this is proportional to the angle α. Therefore this ratio of voltages is proportional to the angle. For a precise determination of angle, it is only necessary to measure this ratio by balancing the bridge for zero indication on the null detector with a precision voltage divider.

Suppose that the shield is moved, causing a change in the values of C_1 and C_2. An error signal will then develop in the null detector because of the current passing through it. By moving the sliding contact of the voltage divider the bridge is balanced, bringing the null needle back to zero. The balanced bridge gives the voltage ratio, and thus the new angle of the shield.

"The advantage of the method is in the use of a ratio measurement to determine angle," says Dr. Makow. "This makes variations in supply voltages, temperature, and humidity of much less concern, since the effect almost cancels out in the ratio."

A series of very accurate angle measurements were made in cooperation with Dr. George Chapman of the Mechanics Section of NRC's Division of Physics, and the CIRCAP was found to have a standard deviation error of about 0.1 seconds of arc. This represents an accuracy of one part in 6.5 million and can be compared to measuring the distance between Ottawa and Montreal to within the thickness of the human thumb.

"With further refinements we hope to improve these results," says Dr. Makow. "The limits of accuracy are determined by a combination of factors related to such things as the effect of the field around the edges of the shield, the random error in the concentricity of the air bearings, and the accuracy of the bridge circuit."

In addition to its use in angular measurement, the CIRCAP can also be used as an angle positioning device. This is accomplished by connecting the output of the null detector to a servomotor that drives the shield.

"Suppose the voltage divider is set to a ratio different from that of the balance point. This causes a deflection in the null needle," says Dr. Makow, "as there will be a voltage imbalance at the output of the detector. This voltage then drives the servomotor, which in turn moves the shield to a position where the imbalance voltage disappears. The new shield position thus reflects the setting of the ratio, which is a measure of the shield angle."

The CIRCAP thus has two uses. It can be used either to measure an angle by rotating the shield, or to position the shield at a given angle by dialing the desired ratio on the voltage divider.

Because the arc of the capacitors is only 180 degrees and there are electric field distortions at the insulating gaps, the CIRCAP can only measure angles smaller than 180 degrees. To circumvent this problem, one CIRCAP unit is positioned over another with the semicircular shields displaced 90 degrees from each other. By simply switching from one unit to the other as the shield approaches a gap region, accurate measurements can be made through 360 degrees of arc.

Dr. Makow was assisted in the CIRCAP project by two other staff members. Albert Zuidhof who worked on the development of the bridge circuits and by Manfred Paulun who did the mechanical design.

"There are many areas that require very accurate angular measurements and settings," says Dr. Makow. "Astronomy, geodesy, space technology, and precision mechanics are good examples. Many instruments currently in use are based on a precisely divided circle where the division marks are read either optically or electronically. A good instrument in this class is only accurate to within one or two seconds of arc."

"The CIRCAP is a unique instrument in the sense that it measures angle continuously without angular units needed to act as a 'yardstick'," says Dr. Theodore Blachut, Head of the Photogrammetric Research Section. "The only angle division used in the instrument is 180 degrees, being half a circle and defined by the straight edge of the shield going through the centre of the rings."

The CIRCAP has many practical uses. If a telescope is mounted on the central shaft, for example, it can be used as a theodolite for very precise surveys in satellite geodesy or to measure the angles between stars. In conjunction with a laser it can be used to track a spacecraft. The CIRCAP also can be used in industry where accurate angle references are needed to calibrate the units used in production. Because the high accuracy of the CIRCAP is not always needed, it can be built in a simpler, more rugged way with a possible cost advantage over the market competition. At present Canadian Patents and Development Limited (CPDL) has issued licenses to two companies in Canada to begin production of the CIRCAP model, Rab-Dedesco in Ottawa and Valeriote Electronics in Guelph, Ontario.

The importance of an instrument like CIRCAP goes beyond the effect it might have on the technology of angle determination. Any improvement in the accuracy of measurement, whether in angle or any of the other fundamental units, such as distance, time or mass, provides a sounder basis for accepting or rejecting current scientific ideas. Since the basic ideas of science rely on scientific experiment for their validation, their acceptance will be largely determined by the confidence in the measurements. Ultimately it is these measurements that underpin the web of theory binding our picture of the universe together. □ Wayne Campbell